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Anisotropic grain noise in eddy current inspection of noncubic polycrystalline metals

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This letter discusses the role electrical anisotropy plays in the structural integrity assessment of polycrystalline titanium alloys from the standpoint of fatigue crack detection and the related issue of microstructural noise. In eddy current inspection of noncubic crystallographic classes of polycrystalline metals the electric anisotropy of individual grains produces an inherent microstructural variation or noise that is very similar to the well-known acoustic noise produced by the elastic anisotropy of both cubic and noncubic materials in ultrasonic characterization. The presented results demonstrate that although the electrical grain noise is clearly detrimental in eddy current nondestructive testing for small flaws, it can be also exploited for characterization of the microstructure in noncubic polycrystalline materials such as titanium alloys in the same way acoustic grain noise is used for ultrasonic characterization of the microstructure in different materials. © *1998 American Institute of Physics.* [S0003-6951(98)03609-2]

Elastic anisotropy of single crystals plays an important role in ultrasonic materials characterization of polycrystalline materials. Microscopically homogeneous but randomly oriented individual grains make up a macroscopically isotropic but inhomogeneous medium which produces incoherent wave scattering commonly called ''grain noise.'' While acoustic grain noise has an obvious adverse, often prohibitive, effect on ultrasonic flaw detection,[1,2] it can be also exploited for ultrasonic characterization of the grain structure.[3–6] Electric anisotropy exhibited by specific types of crystallographic classes can play a very similar role in electromagnetic testing of polycrystalline metals. All physical properties relating two first-order tensor quantities are characterized by second-order tensors, the directivity of which can be represented by an ellipsoid of revolution.[7,8] Such properties include electrical and thermal conductivity, thermoelectricity, dia- and paramagnetism, and dielectricity. In the most common cubic system, the ellipsoid degenerates into a sphere and these properties become fully isotropic. However, in noncubic materials the same physical properties are inherently anisotropic. In contrast, elastic material properties relate two second-order tensor quantities, therefore they are characterized by fourth-order tensors. As a result, from an elastic point of view, cubic crystals are also anisotropic just like other crystallographic classes.

In nondestructive materials characterization electrical conductivity is usually measured by the noncontacting eddy current method. Neighbor was the first to apply the eddy current method to electrically anisotropic materials and showed theoretically that one can obtain the full conductance tensor from such measurements.[9] Special eddy current coil configurations that allow the simultaneous measurement of electrical conductivity in two principal directions have been developed for texture assessment in plates.[10,11] Just as in the case of elastic anisotropy, the source of electrical anisotropy can be either (i) intrinsic crystallographic anisotropy in single crystals and textured polycrystals or (ii) structural anisotropy caused by oriented reinforcement in composite materials. The latter can be exploited for eddy current assessment of constituent volume fractions in metal matrix composites.[12,13] Grain boundary contributions to the electrical resistivity[14] can cause additional electrical anisotropy in polycrystalline materials with elongated grains aligned in preferred orientation due to thermal or mechanical treatment.

It should be emphasized that, in contrast with elastic properties, the electric conductivity is completely isotropic in cubic crystals which constitute the overwhelming majority of polycrystalline metals; therefore, the role of intrinsic crystallographic anisotropy in eddy current testing has not been investigated in detail. However, less common materials of hexagonal symmetry can exhibit strong electrical anisotropy with significant difference in conductivity between the basal plane and normal to it. Titanium is one of the few structural metals of practical importance, especially in aerospace applications, which preferentially crystallizes in hexagonal symmetry and therefore exhibits strong electrical anisotropy.

Eddy current testing is the most common electromagnetic nondestructive evaluation method and is widely used in the aerospace industry. Small diameter coils combined with a computer controlled scanning mechanism can be readily used for eddy current imaging. The coil impedance is determined by the resistivity of the specimen as measured by the eddy current, which runs parallel to the surface in a concentric circle with the coil. In this way, an eddy current probe measures the average resistivity in a given plane rather than in a given direction. As the probe is moved along the surface, it measures the local average resistivity along the path of the eddy current in the plane of the surface. The resistivity is integrated over the entire probe circumference in the eddy current path, resulting in grain contrast that is proportional to the average resistivity between the different crystallographic planes.

For hexagonal crystals like pure titanium and its most common alloys the axial symmetry around the principal direction (the hexagonal axis) allows the directional dependence of the electrical resistivity to be described over the entire space by two orthogonal axes and the directivity can be represented as an ellipsoid of revolution:

$$\rho(\phi)=\rho_{\perp}\cos^2\phi+\rho_{\parallel}\sin^2\phi, \tag{1}$$

where $\rho_{\parallel}$ and $\rho_{\perp}$ denote the electrical resistivity in the basal plane (plane of isotropy) and normal to it, respectively, and ϕ denotes the angle between the direction of current flow and the normal of the basal plane. It is readily seen from Eq. (1) that in cubic materials the electrical resistivity is fully isotropic due to the balanced symmetry of the lattice structure, i.e., the resistivity becomes a single scalar value and the ellipsoid describing its directional dependence degenerates to a sphere. For eddy current measurements of electrical resistivity in a hexagonally symmetric single crystal, the average surface resistivity can be expressed from Eq. (1) as:

$$\rho_s(\theta)=1/2[\rho_{\perp}\sin^2\theta+\rho_{\parallel}(1+\cos^2\theta)], \tag{2}$$

where θ denotes the inclination angle between the basal plane and the surface of the specimen. For example, in pure titanium $\rho_{\perp}=48\ \mu\Omega$ cm and $\rho_{\parallel}=45.35\ \mu\Omega$ cm, i.e., the resistivity is approximately 6% lower in the basal plane than normal to it.[15] Because of the above described averaging effect of eddy current inspection, the actual grain contrast is expected to be 50% lower in eddy current inspection. In titanium, the average resistivity is approximately 3% lower when the basal plane is parallel to the surface than when it is normal to it.

In order to assess the feasibility of eddy current materials characterization and flaw detection in structural alloys of noncubic symmetry, we carried out two sets of experiments. First, we used an eddy current probe to measure the directional variation of the electrical conductivity in pure single crystals of aluminum, copper, and cadmium; the former two materials consist of a cubically symmetric crystallographic lattice, the latter one consists of a hexagonally symmetric lattice (unfortunately, titanium single crystals cannot be grown to sizes large enough for accurate eddy current conductivity measurements). Second, we used an eddy current scanner to map the electrical grain noise in Ti-6Al-4V titanium alloy specimens of different microstructures.

The Al, Cu, and Cd single crystals used in this study were of random orientation. Each specimen was a solid cylinder of approximately 2 in. length and 0.5 in. diameter, large enough to cut into five sections of varying surface orientation. Eddy current resistivity measurements were taken on the various single crystal sample sets using a Nortec 19e eddy current instrument and a 0.060 in. diam probe at 2 MHz.

The measured data are shown in Figures 1(a)–1(c) as histograms of the probability distributions of the surface resistivity for various surface crystallographic orientations in the three single crystals. For each set, only three surfaces

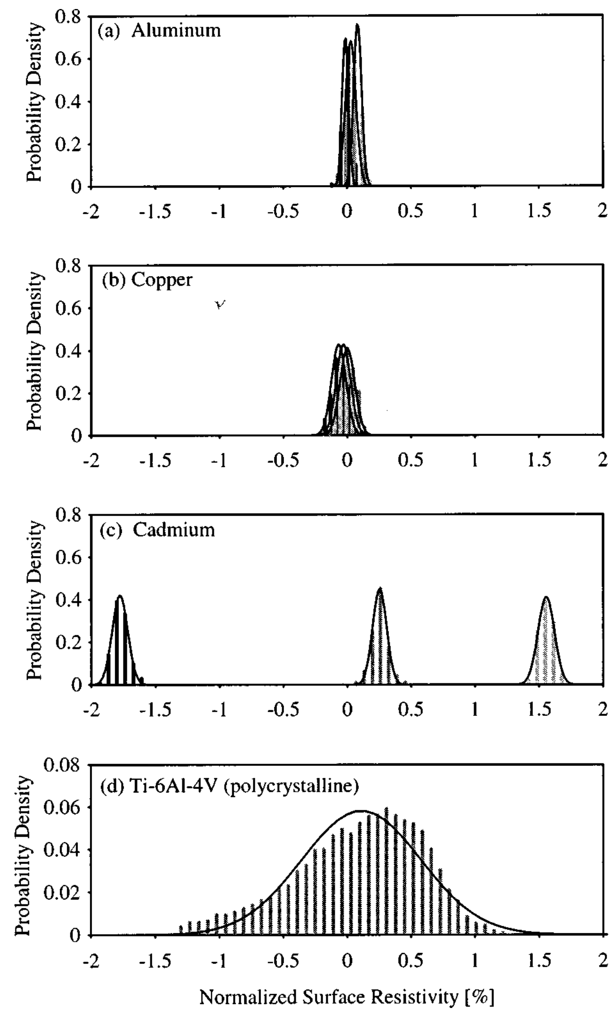

FIG. 1. Electrical resistivity probability distributions for three single crystal surface orientations in (a) aluminum, (b) copper, (c) cadmium, and (d) on the surface of polycrystalline Ti-6V-4V (solid lines are best fitting Gaussian distributions).

showing the largest differences in average resistivity are displayed. It should be noted that these values in average electrical resistivity are subject to a variety of small experimental errors, including thermal drift from the instrument or sample, probe alignment and an associated probe rocking effect, inevitable thickness and edge effects, etc., hence the variability in the data. These factors were considered during the data collection and efforts were taken to minimize their effects. The data from Figure 1(c) clearly demonstrates the crystallographic dependence of the electrical resistivity in cadmium representing noncubic materials, as opposed to the lack of separation demonstrated by cubic copper and aluminum in Figures 1(a) and 1(b). In the cadmium crystal the values of electrical resistivity are $\rho_{\perp}=8.3\ \mu\Omega$ cm and $\rho_{\parallel}=6.8\ \mu\Omega$ cm, a relatively large difference of approximately 22% between the basal plane and the normal to it.[8] Due to the averaging effect, the most extreme resistivity separation which could be expected in Cd by eddy current measurement is approximately 11%. The average resistivity variation present in the randomly cut Cd samples was clearly measurable with a maximum variation of approximately 3% in resistivity. Considering that the five flat surfaces which were large enough for accurate conductivity measurements without adverse edge effects did not necessarily coincide or even

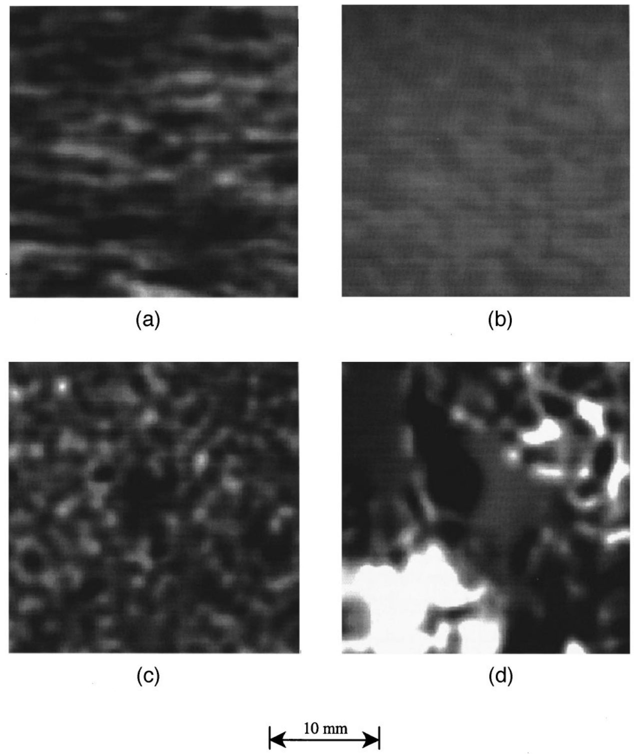

FIG. 2. Scanned eddy current images of different Ti-6Al-4V microstructures: (a) the as received billet microstructure showing texture related features in the horizontal direction; (b) solution treated and annealed very fine microstructure; (c) equiaxed beta annealed microstructure; and (d) heat-treated coarse grain structure with large colonies (dimension 1 in.×1 in.).

lie close to the principal planes of maximum separation, the measured variation is reasonable. It should be emphasized that the primary purpose of these experiments was simply to demonstrate that the intrinsic electrical anisotropy of hexagonal materials can far exceed the sensitivity of eddy current inspection. A more quantitative experimental study based on accurate orientation measurements via x-ray diffraction and a much smaller eddy current probe to avoid edge effects is currently underway.

Because of our particular interest in nondestructive testing of high-strength titanium alloys by eddy current methods, a special attempt was made to obtain the same type of data from a pure alpha (hexagonal) phase Ti single crystal. However, due to the inherently small size of the available Ti single crystals, it was not possible to collect data actually representative of the material's electrical resistivity due to edge affects, which tend to diminish the accuracy of the measurements. Moreover, in titanium, the maximum difference in average resistivity measured using the eddy current method is expected to be only about 3%, i.e., only one fourth of the corresponding variation in Cd. Nevertheless, based on the results from the Cd crystal sample, the evidence of electrical anisotropy in noncubic crystalline materials is clearly supported. To further demonstrate this point, Figure 1(d) shows the probability distribution of the surface resistivity for a Ti-6Al-4V polycrystalline specimen. As expected, there is a significantly wider variation in the resistivity from point to point than on single crystals, which will be shown later to be caused by the relatively coarse grain structure.

The macroscopic inhomogeneity of the microstructure in polycrystalline Ti-6Al-4V can be clearly observed on the eddy current images shown in Figure 2, which correspond to a 1 in.×1 in. area on the samples. Figure 2(a) shows a typical as received billet microstructure with texture related features in the horizontal direction. The specimen shown in Figure 2(b) has been solution treated and annealed to produce a very fine grain structure which is not resolved by the 0.060 in. diam probe. Figures 2(c) and 2(d) show an equiaxed beta annealed microstructure and a heat-treated, coarse grain structure with very large colonies, respectively.

To conclude, some interesting parallels can be observed between the reported electromagnetic approach and conventional ultrasonic evaluation methods. Ultrasonic techniques can be used to exploit the fact that in polycrystalline materials, grain to grain differences in crystallographic orientation and the presence of grain boundaries provide a source for scattering of ultrasonic energy. In ultrasonic flaw detection, the acoustic grain noise is clearly detrimental due to reduced detection threshold. Likewise, electromagnetic inspection techniques benefit from the fact that noncubic systems exhibit electrically anisotropic properties, allowing for microstructural characterization, and suffer from the fact that the electrical scatter originating from varying local resistivity raises the noise floor, thereby reducing flaw detectability. Although the electrical anisotropy of noncubic crystals is a well known physical fact, to the best of our knowledge, the significant role played by the microscopic electrical anisotropy of individual grains in the macroscopic eddy current response of the polycrystalline material has never been pointed out or investigated in any depth.

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